FATIGUE CRACK PROPAGATION UNDER SPECTRUM LOADING

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Abstract

This project involved development of a method to predict the fatigue crack propagation process in thin-walled aircraft structural components under flight-by-flight loading. Extensive experimental test results provided the input for software development. They yielded evidence pointing to the complex nature of crack growth under spectrum loading and also provided the basis for procedures adopted for life prediction. A simple engineering method is proposed for estimation fatigue crack *propagation life wider random loading. Predictions are based on test data obtained under constant amplitude loading. Prediction accuracy favourably compares with that of available techniques. Computation time is extremely small, enabling the use of desktop computers for life predictions.*

The project received substancial funding from the Aeronautical Research and Development Board. *This* document constitutes *the final consolidated technical report on the project which carried NAL numbers MT-107/MT-0-157 under ARDB grants-in-aid Aero/RD-134/100/10/80-81/262.*

Introduction

At the commencement of this project in 1980-81, variable amplitude fatigue crack propagation (FCC) had already been studied quite extensively. Many load interaction mechanisms had been identified which contribute to acceleration/retardation in crack growth and related non-linearity in the damage accumulation process, A review of the various mechanisms of crack growth and load interaction can be found in [1]. The review also describes various existing prediction models for FCP under variable amplitude loading. Fatigue crack closure has been identified as the predominant load interaction mechanism. As would be expected, prediction models based on crack closure have been found to be more accurate.

Four major drawbacks can be identified in available prediction techniques:

1. No reliable technique has been proposed for accurate assessment of crack closure stress, which is a major variable in calculations.

2. Cycle-by-cycle estimates of crack extension can take up enormous computer resources.

3. Most, available prediction techniques do not include procedures for cycle counting - an essential requirement while dealing with random load histories.

4. None of the methods can deal with dK/da effects on crack growth rate under spectrum loading.

Inaccuracies and other problems encountered while using existing methods for FCP life prediction can largely be attributed to one or more of the reasons listed above.

The objectives of this project were:

1. Development of an experimental technique for accurate assessment of crack closure stress level.

2. Setting up of a test system to carry out FCP tests under spectrum loading with both stress as well as K-control.

3. Experimental validation of cycle counting techniques for FCP analysis under random loading.

4. FCP studies on an Al-Cu alloy sheet material under constant amplitude and flight simulation loading.

5. Development of an engineering method for FCP life predictions under random loading.

6. Validation of the prediction method through full-scale tests on Gnat Aircraft wings discarded by the IAF.

Regretfully, the last objective could not be achieved due to the inavailability of the Ajeet test rig for the purpose. Validation of the proposed technique was therefore carried out through comparison with other available methods on the basis of data in the literature. All the objectives listed above as well as the modified sixth one have been achieved as described below in some detail. A more elaborate description of the work can be found in the attached list of references.

Experimental and Analytical Procedures

Analysis of Results

Experimental Technique for Crack Closure Stress Measurement

A technique was developed for accurate estimates of crack closure stress [2]. It involves transmission electron fractography of fatigue fractures obtained under specially designed load sequences. Some typical results from the study appear in Fig 1. Using the technique, crack closure stress, Sop, was measured in a few Al-Cu alloys of different thickness. The study provided reliable and accurate Sop estimates. It also showed that crack closure stress changes with thickness and varies along the crack front.

A method was developed for binary coded event registration on fatigue fractures [3]. It involves application of specially designed load blocks which leave behind unique striation patterns on the fracture surface. These can later be identified by electron fractography. This technique offers a powerful tool to 'append' the block number to each measurement of crack closure.

System for FCP Tests under Spectrum Loading

A 25-ton INSTRON servohydraulic test system with PDP 11/23 computer was installed at NAL in 1982. All the tests for the project were to be carried out on this system. For this purpose, a realtime computer software package was developed. Refs 4,5 describe this effort in detail.

Among the salient features of the system are:

1. Fully automated FCP testing including measurement of crack length and crack closure stress level.

... Tests under any given load sequence including constant amplitude, programmed and random flight by flight loading.

5. Testing under both stress control as well as K control with any predefined K variation with crack length.

Towards the completion of the project, an additional feature was included into the system. It permits on line fatigue cycle analysis during tests under random loading.

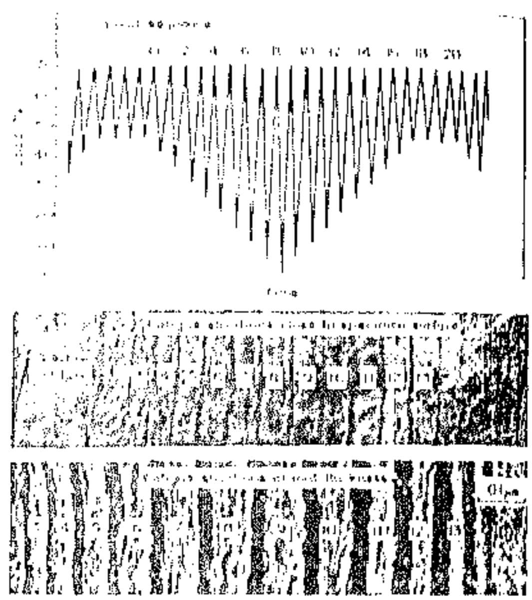


Fig.1. Crack closure is estimated from the number of equally spaced striations. Note the reduced closure stress at mid thickness as opposed to surface region (Al-Cu alloy).

Fig. 2 shows the test system and computer. The COD gage used for compliance based crack length and closure measurements, appears in Fig. 3. The algorithm for K controlled testing appears in Fig. 4, while Fig. 5 shows the procedure for automated crack closure stress estimation. The flow chart for on line fatigue cycle analysis appears in Fig. 6. On line fatigue cycle analysis permits accelerated fatigue testing without compromising the quality of results.

Validation of Cycle Counting Techniques for FCP Analysis

A typical sequence of g loads on a combat aircraft is shown in Fig. 7. One cannot readily identify load cycles from such a sequence of random peaks. All available expressions for crack growth rate refer to closed cycles of

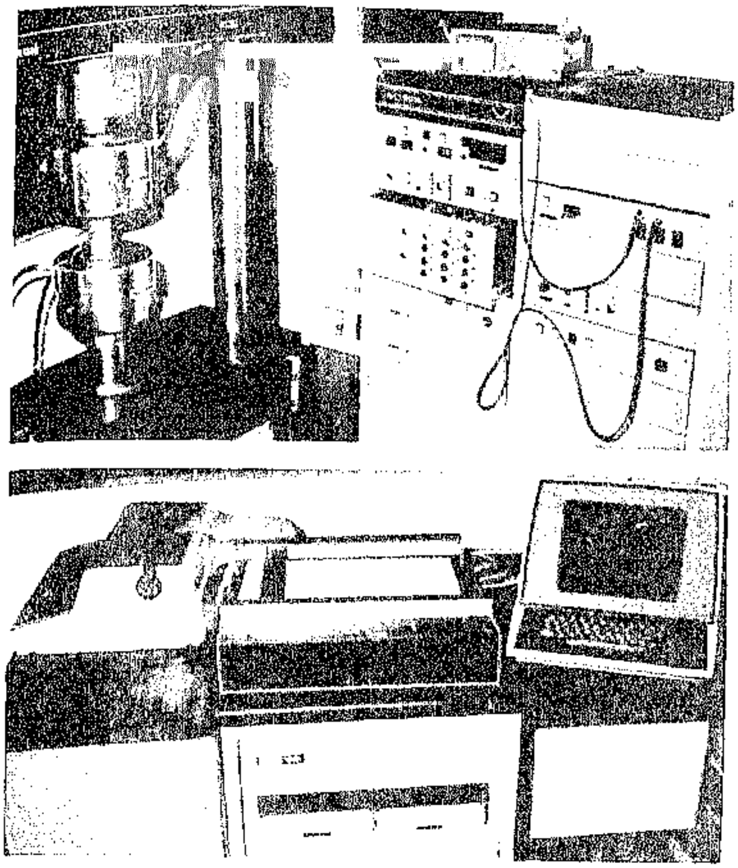


Fig.2. INSTRON 1345 servohydraulic fatigue testing machine (top) with PDP 11/23 computer system (bottom).

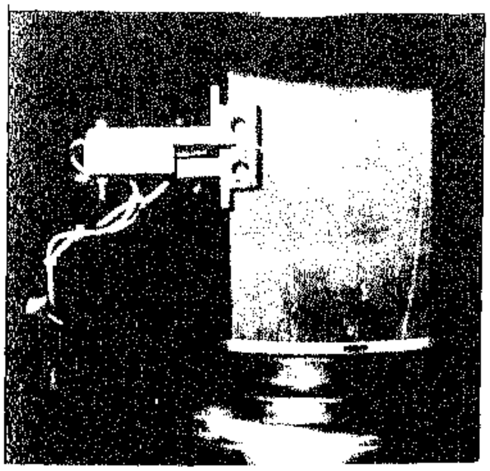


Fig.3. (COD) gage used for compliance measurements

constant amplitude loading. One cannot therefore extend these to the type of loading in Fig.7, without first identifying closed cycles in a given load history. This exercise in referred to as cycle counting.

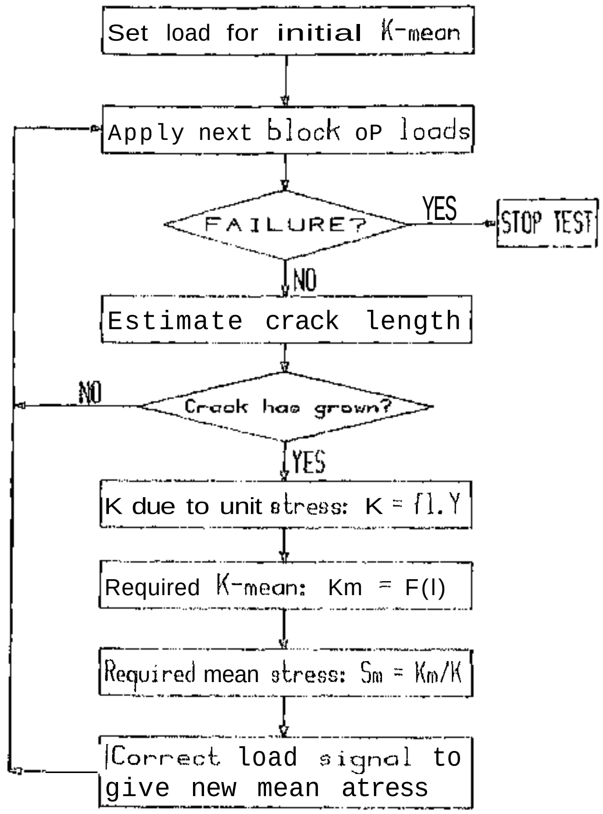


Fig.4. Flowchart for K-controlled testing

A number of techniques are available for cycle counting. The most popular *of* these is the Rainflow technique. Range counting is also widely used, particularly in FCP analysis. A fractographic study was carried out to validate these two techniques [6]. The fatigue fractures were obtained under specially designed programmed load blocks. Typical results appear in Fig.8, which also provides a schematic of the procedure for analysis. These results provided conclusive evidence pointing to the validity of the Rainflow cycle counting technique. This formed the basis for the development of a new FCP life prediction method. It also provided the basis for incorporating on-line fatigue cycle analysis into the software package for automated FCP testing. The study also showed that errors in excess of 300% can result if Range counting is used.

Fatigue Crack Propagation under Stress and K-controlled Spectrum Loading

Fatigue crack propagation was studied in 1mm and 5mm thick D16AT Al-Cu alloy sheet material under stress and K-controlled flight-by-flight combat aircraft spectrum loading.

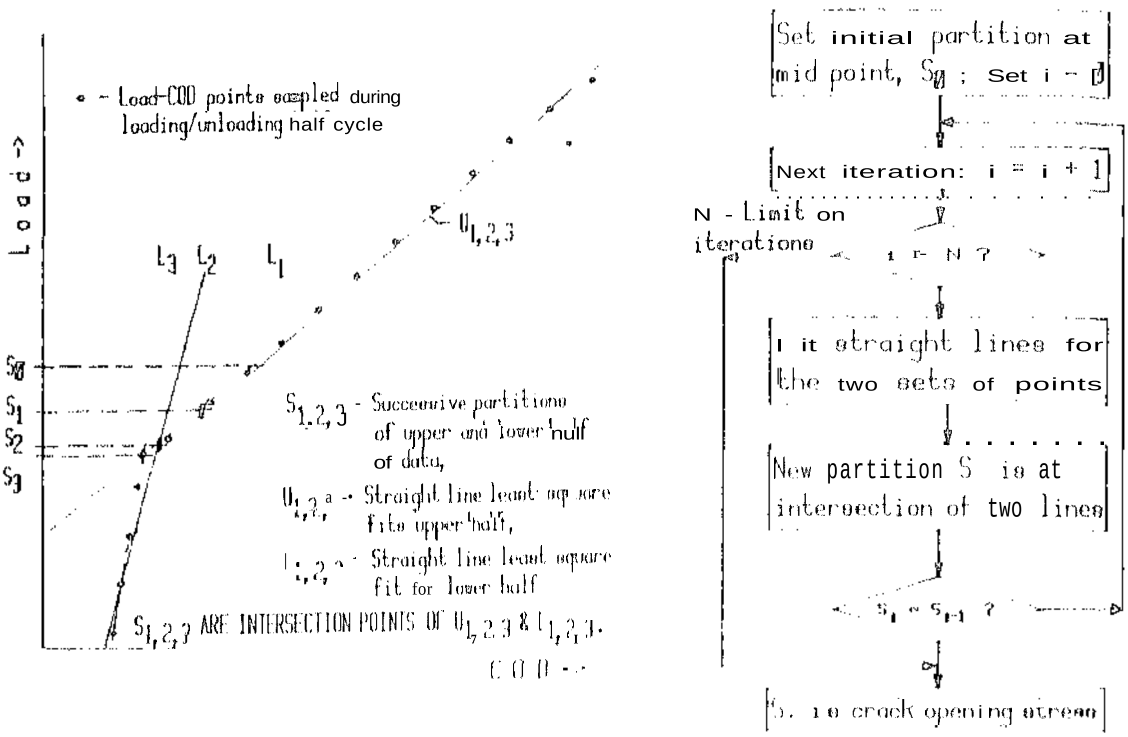


Fig.5. Iterative technique for automated crack closure stress measurement

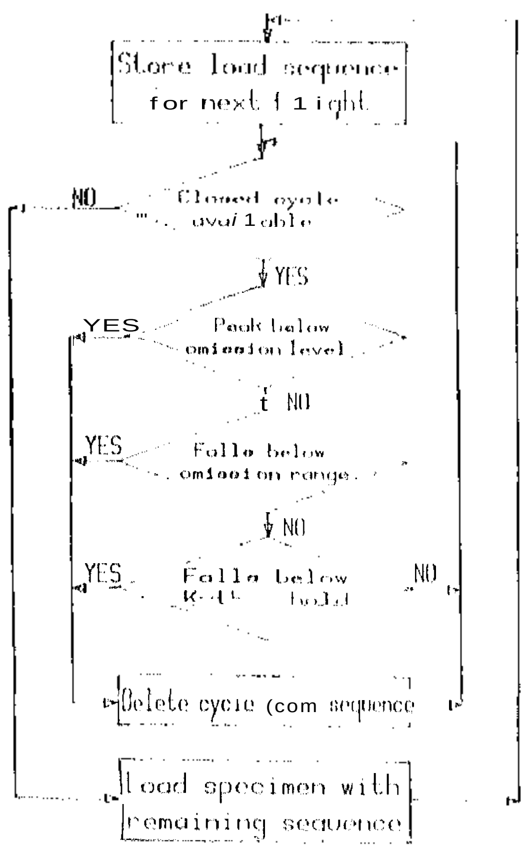


Fig.6. Flow-chart for on-line fatigue cycle analysis.

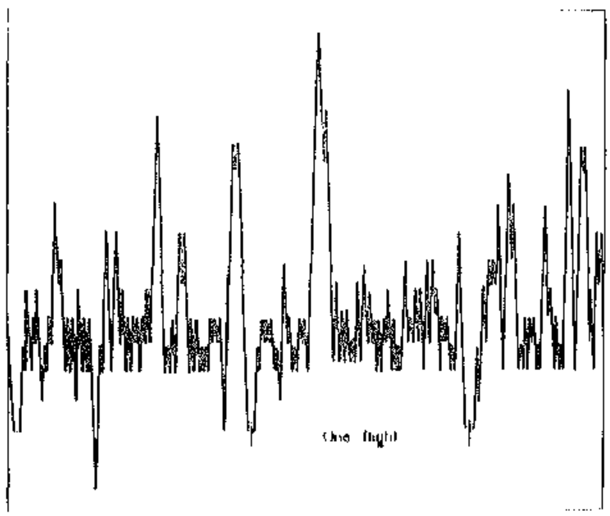


Fig.7. Typical sequence of g loads on a combat aircraft

The load spectrum shown in Table 1, which was derived from flight data on an IAI aircraft was used in the tests. Ref. 7 describes this study in detail. The tests were carried out on 75mm wide SE(T) specimens. Typical test results appear in Fig. 8. The test results indicate a strong influence of dK/da on crack growth rate, particularly at low stress intensity levels. At identical K and dK/da, crack growth rate appears to be affected also by crack length/net stress. The study shows, that to obtain realistic

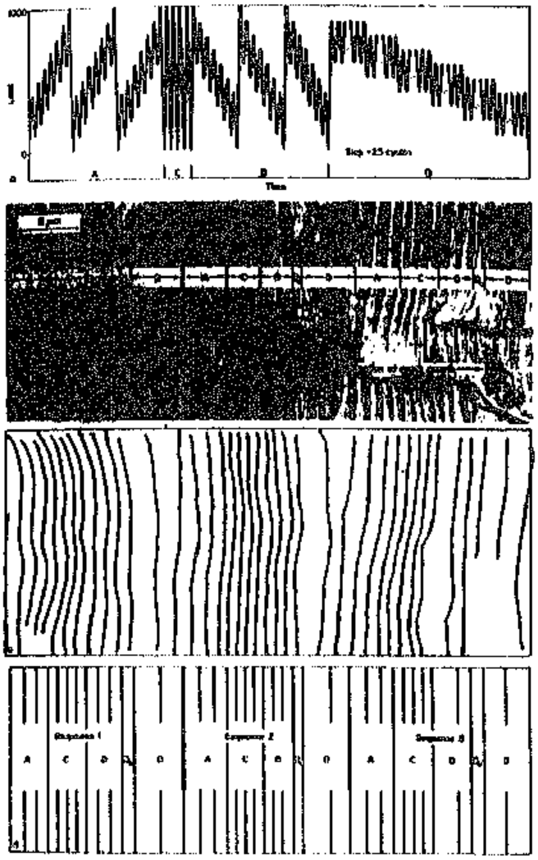
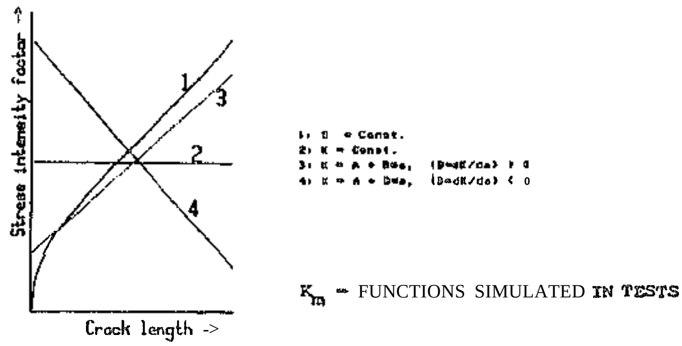


Fig.8. (a) Complex load sequence, (b) Striation pattern, (t?) Digitized pattern and (d) Equivalent pattern.
Analysis of equivalent pattern confirms validity of Rainflow cycle counting technique.



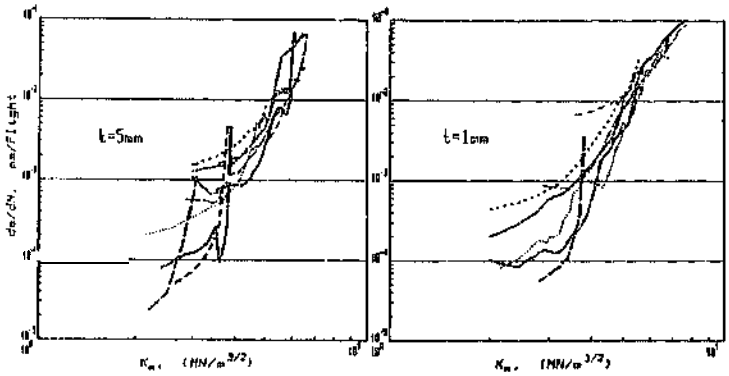


Fig.9. da/dN vs Km from tests at different levels of stress and K-functions

crack growth rates under spectrum loadinq, representative stress levels as well as crack geometry should be used in tests. At the same time, the required K-function can also be simulated on any standard specimen geometry through K-controlled testing.

Table - 1.

Markov matrix of g-load spectrum for a combat aircraft. (Covers 533 flights)

g:	-2.5	-2.0	-1.5	-1.0	-0.5	0.0	0.5	1.0	1,5	2.0	2.5	3,0	3,5	4.0	4,5	5,0	5.5	6.0	6.5	7,0	7.5	8.0	0,5	9.0
-2.5	0	2	0	1	0	0	0	3	6	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0
-2.0	2	0	1	0	0	1	1	27	24	13	6	3	9	3	1	1	1	D	2	0	0	0	0	0
-1.5	0	1	0	1	3	0	2	39	31	9	6	11	6	3	1	2	2	0	1	0	2	0	0	0
-1.0	0	1	1	0	2	2	2	22	23	14	2	0	0	1	1	0	0	11	0	0	0	0	0	0
-0.5	0	0	3	2	0	(1	19	39	45	17	8	6	2	6	2	3	2	0	0	1	0	0	0	0
0.0	0	1	1	2	7	0	60	172	332	122	63	55	44	27	21	13	13	5	5	1	3	1	1	1
0.5	0	2	1	2	22	57	0	2410	3100	1123	505	39)	260	179	121	95	63	60	29	19	7	6	5	0
1.0	6	37	44	18	44	461	2402	0	1773	139B	580	312	196	120	79	52	27	19	12	9	5	0	2	0
1.5	4	11	23	19	35	322	3487	1741	0	564	529	207	74	34	12	6	8	2	2	1	0	1	0	0
2.0	1	18	9	16	19	144	1103	1363	511	0	336	324	116	35	19	10	2	3	1	0	1	0	0	0
2.5	0	7	4	4	6	83	594	590	531	296	0	196	194	55	28	11	3	4	0	0	1	1	0	0
3.0	0	2	13	2	9	57	357	334	197	339	195	0	14D	118	44	15	4	3	1	1	0	0	0	0
3.5	1	9	9	1	0	32	260	206	90	126	104	125	0	75	76	23	6	1	4	1	0	0	0	0
4.0	2	1	3	0	5	26	167	104	47	44	63	126	68	0	43	44	9	5	2	1	2	0	0	0
4.5	0	1	2	1	0	17	111	89	25	17	33	45	70	37	0	26	23	7	1	0	0	0	0	0
5.0	0	1	3	1	1	13	72	61	17	12	9	18	30	44	17	0	0	1!	5	1	0	0	0	0
5.5	0	0	4	0	0	5	53	35	9	4	3	3	9	16	21	9	0	3	5	3	0	1	0	0
6.0	0	0	0	0	0	14	30	24	9	6	5	3	5	4	10	9	4	0	0	3	0	0	0	0
6.5	0	1	0	0	0	3	24	21	2	0	0	0	2	2	5	4	5	1	0	2	2	0	0	0
7.0	0	0	0	1	0	3	15	5	0	3	1	4	1	2	2	2	3	2	2	[illegible]	2	0	0	0
7.5	0	0	0	0	0	3	7	4	2	0	0	2	0	1	1	1	0	0	2	2	0	0	0	0
8.0	0	0	0	0	0	2	5	2	0	0	0	0	1	0	9	0	0	0	0	0	0	0	0	0
8.5	0	0	0	0	0	0	4	3	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0
9.0	0	0	0	0	8	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table - 2.
Matrix of Rainflow counted cycles (lower half) and effective load cycles (upper half) from spectrum in Table 1.

g	0.5	1,0	1,5	2,0	2,5	3.0	3.5	4.0	4,5	5,0	5,5	6,0	6,5	7,0	7,5	8,0	B.5	9.0	9,5	19.0	10.5	11.0	11.5	12.0	g
9.0	0	0	D	0	0	D	0	0	0	0	0	0	1	0	0	0	0	0	B	0	0	B	0	0	-2.5
8,5	D	0	a	0	0	0	0	0	B	0	0	9	•i	B	0	0	D	0	0	0	0	0	0	2	-2.0
8,0	0	0	0	0	0	0	0	0	0	0	ilx	0	0	0	0	0	0	0	0	0	0	0	0 E	1	-1.5
7,5	0	2	0	0	0	0	1	0	B	20	X 0	0	0	0	0	0	0	0	0	B	0	0	1	1	-1.0
7.0	0	2	3	2	0	2	1	1	33	0	0	0	0	0	0	0	0	0	0	0	0	0	31	2	-0.5
6.5	0	5	4	1	2	2	1	53	0	0	0	0	0	0	0	0	0	0	0	0	1	0	2	0	0.0
6.0	0	10	7	4	3	3	92	0	B	0	Q	B	0	0	0	0	0	0	0	1 (3)	1	2	20	60	0.5
5.5	0	23	10	6	4	119	Xg	0	0	D	0	0	0	0	0	E	0	3	27	40	22	3V	472	2409	1.0
5.0	g	44	23	15	193	0	0	0	0	‖	0	ff	0	0	C	0	4	11	24	19	41	322	3449	1773	1.5
4.5	0	76	44	205	XD	0	0	0	0	0	0	0	D	0	0	3	16	10	14	19	115	1125	1398	564	2.0
4.0	0	1118	463	0	0	0	0	0	0	0	0	0	Q	0	D 0	16	10	2	7	BO	555	500	529	336 A	2.5
3.5	B	1910	0	0	0	0	0	0	0	0	0	0	0	0	3	11	3	4	64	301	312	207	324	196	3.0
3.0	B	0	0	0	0	0	0	0	0	g	0	0	0	10	6	0	8	38	260	196	74	116	194	140	3.5
2,5	0 A'	0	0	0	0	0	0	0	0	B	0	0	2	7	2	5	24	179	120	34	35	55	118	75	4.0
2,0	D	0	0	0	0	g	0	0	0	0	1	0	1	1	0	17	126	79	12	19	29	44	76	43	4.5
1.5	0	0	0	0	0	0	0	Ox	0	0	0	3	0	4	16	92	52	6	10	10	15	23	44	26	5.0
1.0	0	1	0	0	0	B	0	0	B	0	Y2	0	3	11	64	2?	0	2	3	4	6	10	23	9	5.5
0,5	0	0	0	0	0	C	0	0	1	B	0	0	5	57	19	2	3	5	3	3	4	7	10	4	6.0
0.0	O	i	0	0	6'	0	0	0	0	0	0	5	32	13	2	1	0	1	2 (1)	2	1	4	5ft)		6.5
-0,5	B	0	0	Q	0	0	1	1	0	g	6	14	0	1	1	1	1	1	2	0	2	3	2	2	7.0
-1.0	0	0	0	0	0	B	2	0	B	2	10	8	1	0	0	0	0	1	0	0	0	0	2	2	7.5
-1.5	B	0	0	1	1	0	0	0	2	6	1	0	0	8	0	0	0	0	0	‖	0	0	0	0	8.0
-2.0	0	0	0	0	0	0	0	3	4	2	0	0	0	0	t	B	B	0	0	0	0	0	0	0	8.5
-2,5	0	0	0	0	0	‖	0	0	1	0	0	0 C	0	*	0	D	0	0	0	0	0	0	0	0	9.0
g	12.0	11.5	11.0	10.5	10.0	9,5	9,0	0.5	8.0	7,5	7.0	6.5	6.0	5.5	5.0	4.5	4.0	3,5	3.0	2.5	2.0	1.5	1.0	O.S	g

The constant amplitude growth rate and crack closure data from this study provided the material constants to be used in the proposed FCP life prediction technique. The observations on dK/da effects provided the basis for correcting Sop values in life estimates.

Development of an Engineering Method for FCP Life Prediction under Random Loading

This stage of the project may be termed as the most important from the viewpoint of project objectives. A simple engineering method for FCP life prediction was developed based on observations made during the experimental studies. Ref. 8 describes this in detail. The salient features of the method are:

1. Constant amplitude test data by way of growth rates versus stress intensity and crack closure levels constitute the material constants.

2. dK/da effects are accounted for by correcting closure stress for rate of change of plastic zone size with crack length.

3. Cycle-by-cycle FCP estimates involving enormous computer time art) not, carried out. Instead, average growth rates are estimated for a matrix of Rainflow counted cycles derived from the load spectrum of interest (See Table 2).

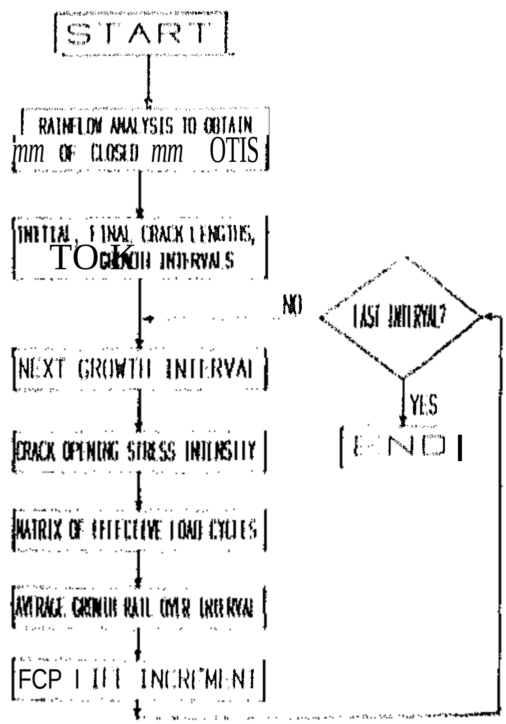


Fig.10. Flow chart for FCP life prediction under random loading

The flowchart for life estimates appear in Fig. 10,

Table - 3.
Accuracy of FCP life predictions - a comparison of various methods.

No	Mission type. stress (MPa)	Test life (cycles)	JC(1)	CHH	;N	US:	J8	JC(2)	Proposed method
			Prediction ratios, N-pred/N-test using various methods						
1.	Fighter (A-A) DLS=138	115700	1.21	2.13	1,01	1.18	1.84	1.46	1.03
2.	Fighter (A-A) DLS=207	58585	0.76	1,35	0.67	0.97	1.26	0,91	0.69
3.	Fighter IA-A) DLS=276	18612	0,79	1,36	0,64	1.06	1,39	0.93	0.70
4.	Fighter (A-G) DLS=138	268900	1.13	1,47	1.47	1.27	1.65	1.37	1.12
i,	Fighter (A-G) DLS=207	95442	0.77	1,04	0.89	0.94	1.38	0.96	0.84
6.	Fighter IA-G) DLS=276	36367	(.64	0.82	0.65	1.02	1.24	0.80	0,70
7,	Fighter (I-N) DLS=207	380443	0.74	1.25	2.52	1.55	2.13	1.39	1.06
I,	Fighter (I-N) DLS=276	164730	0.58	0.94	1.47	1.35	1,75	1,12	0.85
9,	Fighter (C) DLS=138	210151	1.06	1.97	1.17	1.24	1.84	1,33	0.99
II,	Fighter (C) DLS=207	65627	0.79	1.42	0,70	1.01	1.49	1.01	0.79
II,	Fighter (C) DLS=276	22102	0.77	1.42	0.69	1.03	1,53	0.98	0.75
12.	Transport(C) MSS=96.6	1359000	1,78	-	0,76	1.08	2.65	1.31	1.11
13.	Transport(C) MSS=135.2	279000	1,53	"	1.25	0,92	2.25	1.14	1.05
	Average prediction ratio		0.96	1.38	1.07	1.11	1,74	1.13	0,90
	Standard deviation		9.36	0,42	0.33	0,20	0.42	0,22	0.16
	Maximum prediction ratio		1.78	2.13	2,52	1,53	2.65	1.46	1,12
	Minimum prediction ratio		0.58	0.82	0.64	0.82	1.24	0.88	0.69

Codes:

JC(1) - Chang's method No.1.
JC(2) - Chang's method No.2.
CM - Hudson's method.
JN - Newman's method.
WSJ - Johnson's method

18 - Rudd and Engle's method.
DLS - Design limit stress.
MSS - Maximum spectrum stress.
A-A - Air-to-Air.
A-G - Air-to-Ground.
I-N - Instrumentation and Navigation
C - Composite

Validation of FCP Life Prediction Technique

ASTM STP 748 describes a round robin study carried out in the USA to evaluate five popular FCP life prediction techniques. They were evaluated against experimental data obtained under 13 different aircraft load sequences. Predictions were made on the basis of constant amplitude test results for the same material - 4mm thick 2219 Al alloy.

The purposed method for FCP life prediction was also evaluated using the same data. Table J summarizes the results of the comparative evaluation. It follows from the table that the proposed technique is at least as good as the beat available one. Further, considering that its requirements of computer resources are negligible as opposed to cycle-by-cycle estimates, the proposed method con be rated as superior from the viewpoint of practical application. Incidentally, all calculations were carried out on the HP9825 desktop computer which forms part of the Aircraft Flight Data Analysis System (AFDAS) at NAL.

Concluding Remarks

The project provided an opportunity to carry out forward looking research in the area of fatigue crock propagation. Apart from achieving the stated objectives, the project has made a useful contribution to studies on metal fatigue. Among the achievements that deserve particular mention are:

1. A new method was developed for crack closure measurements and binary coded event registration.

2. For the first time, a test system was developed for K-controlled testing under spectrum loading with on-line fatigue cycie analysis.

3. A novel approach was devised for validation of Rainflow cycle counting in FCP analysis.

4. A simple engineering method for FCP life prediction was developed. It can be implemented on desktop microcomputers.

It must be noted that the outputs of this project constitute a useful input to new in-house and ARDB sponsored projects at NAL. For example the experience gained during relatime software development is now being used in the development of microprocessor based controllers for fatigue test equipment. The ongoing project on the study of short cracks at notches extensively uses the techniques developed for crack closure measurement and binary coded loading. It is expected that FCP test results obtained on the D16 AT alloy sheet material under combat spectrum loading will from a useful input to the ongoing programme of full-scale fatigue life evaluation of an airframe.

Acknowledgement

Financial assistance provided by ARDB is gratefully acknowledged. ARDB support and encouragement was crucial in participating at major international conferences in India and abroad where the results of our work were presented. The constant encouragement and sympathy shown by the project monitors, Dr. R. Peravali and Prof K. Rajaiah went a long way in leading the project to a successful completion. Obviously, this work would not have been possible but for the support provided by NAL in various ways including facilities, manpower and expertise of the Fatigue and Fracture Group (Dr. K.N. Raju), Electron Microscopy (Dr. R.V. Krishnan), Materials Workshop (Mr Narayanaswamy), Graphic Arts (Mr C. Rajagopal) and others.

References

1. K.N. Raju and R. Sundar, Unified Approach for Modelling Fatigue Crack Growth and Some Observations on Behaviour under Flight Simulation Loading, NAL TM-MT-7-84 (Also Proc. ICF6, New Delhi, Dec. 1984).

2. R. Sunder and P.K. Dash, Measurement of Fatigue Crack Closure through Electron Microscopy, Int. J. Fatigue, April 1902, Vol.4, pp.97-105.

3. R. Sundar, Binary Coded Event Registration on Fatigue Fracture Surfaces, NAL-TM-MT-8-82 (Presented at SEECO'83, London, March 1983).

4. R. Sundar, Automated Batch Processing of Fatigue Crack Propagation Tests, NAL-TM-MT-10-83, (Also, Proc. ICF6, Now Delhi, Dec. 1984).

5. R. Sunder, System for Automated Cra Growth testing under Random Loadir NAL-TM-MT-8-84 (To appear in Int. Fatigue, Jan. 1985).

6. R. Sunder, S.A. Seetharam and T.A. Bha karan, Cycle counting for Fatigue Cra Growth Analysis, Int. J. Fatigue, Vol. Jul. 1984, p.147.

7. R. Sunder, Fatigue Crack Propagati under Stress and K-controlled Spectru Loading, NAL-TM-MT-2-84 (Presente at Fatigue '84, Birmingham, Sept. 198

(). R. Sunder, Crack Growth under Rando Loading - Fatigue Cycle Analysis for Testi and Life Estimates, NAL-TM-MT-9-((Presented at Int. Symp. on Strength, Kie Sept. 1984).